EIC Detector R&D Report

The eRD108 Consortium

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Project ID: eRD108

Project Name: R&D on cylindrical MPGDs towards an EIC detector

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1 Introduction

This document reports R&D activities on cylindrical Micro-Pattern Gaseous Detectors (MPGDs) for the tracking system of the EIC project detector ePIC. Two types of technologies have been developed: Micromegas (MM) and micro Resistive-Well (µRWELL).

The main purpose of this R&D effort has been the development of lightweight, large–area, cylindrical MPGD detectors equipped with 2D readout strips for the ePIC experiment.

1.1 The ePIC Tracking system

The tracking system of the ePIC experiment is shown in Figure 1. The Silicon Vertex Tracker (SVT), based on the ALICE-ITS3 MAPS technology, is composed of five barrel layers that covers the mid-rapidity region and five disks on both forward and backward directions, covering rapidities up to $|\eta| < 3.8$. The SVT will provide spatial resolutions good enough to achieve the required momentum and pointing resolutions. The tracking system is completed by a set of MPGD detectors whose main purpose is to address the following risk mitigations:

- Pattern recognition performance of ePIC trackers based on Si detectors alone is insufficient with the limited number of silicon layers.
- The slow integration time of the Si trackers means that the ePIC trackers need to be complemented by MPGD layers to provide additional fast timing capabilities.
- Improve the track pointing resolution at the particle identification detector surfaces.

The three ePIC MPGD subsystems are:

- The μRWELL barrel outer tracker (μRWELL-BOT), sitting in front of the hpDIRC detector (at a radius of 73.5 cm), consists of 24 1.7 m-long (the active area) planar modules organized in 12 sectors.
- The μRWELL end-cap trackers (μRWELL-ECT), consisting of two set of planar disks around the beam pipe, two covering the covering the forward region (z=150.5 cm and z=163.5 cm) and two covering the backward region (z=-112.5 cm and z=-122.5 cm).
- The cylindrical Micromegas barrel layer (CyMBaL), covering $|\eta| < 1.5$, wraps around the SVT at a radius of 55cm.

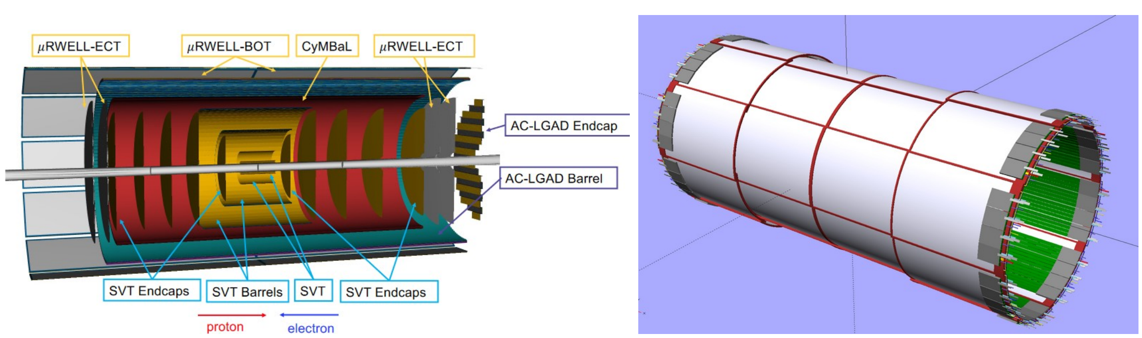

Figure 1: (left) ePIC tracking system. (right) Preliminary CAD design of CyMBaL.

2 Cylindrical Micromegas Barrel Tracker – CyMBaL

In the current design of the ePIC tracking system, the inner MPGD layer, i.e. CyMBaL, sits at a radius of 55 cm and covers, in the longitudinal direction, from z=-105 cm to z=143 cm. CyMBaL consists of 32

identical Micromegas tiles, bent at two different radii of 55 cm and 57.5 cm, that overlaps in the azimuthal (8 modules) and in the longitudinal directions (4 modules) to provide full acceptance coverage, as shown in Figure 1. Due to the space limitations imposed by the ePIC tight integration, the front end boards (FEBs) will have to be attached to the modules. In order to avoid excessive material budget in the active region, it has been decided to place all the FEBs at the periphery of CyMBaL: the inner modules will be connected to the FEB via light micro-coaxial cables. Each module will be equipped with 1024 readout channels that will provide a 2D hit information and readout by the SALSA chip that is being developed within eRD109. The current size for a module is 67x48 cm^2, with an active area of about 61x46cm^2. The base technology chosen for the CyMBaL modules is the cylindrical resistive Micromegas developed for the CLAS12 Barrel Micromegas Tracker (BMT) at JLab. This technology provides low material budget ($\sim 0.5\% X/X_0$) that has been designed to work in high magnetic field (5 T) and high charged particle fluxes.

The ongoing R&D aims at optimizing the 2D readout pattern for CyMBaL to obtain spatial resolutions around 150 μm with orthogonal strips of about 1mm pitch and at building a functional size 1:1 prototype.

2.1 What was planned?

The plan for the FY24 cycle is twofold.

The finalisation of the FY23 program:

- Finalisation of the analysis of the 2023 beam test and setup the cosmic test bench with the addition of the silicon telescope with the goal of characterizing different 2D readout patterns.
- Design, production and tests of a large-scale prototype with the chosen 2D readout. In order to save engineering time, it was decided to start from the mechanics of a CLAS12 BMT tile. The active area of a BMT module is about 45x45cm2, comparable with the expected size of CyMBaL modules. The bending radius will be about half of the CyMBaL modules.
- Design and production of a scale 1:1 mechanical mock up, to test the mechanical properties of a larger detector compared to the BMT modules.
- Completion of tests on resistive patterns (plain, strips in several directions) combined with several read-out patterns with the small prototypes and preparation for a second beam test.

The FY24 proposal included two activities aiming at addressing some needed amelioration:

- In order to compensate the loss in spatial resolution at large angles, one might reduce the conversion gap from 3 mm to 1 mm. Working with a thin gap, though, reduces the number of primary electrons and therefore the efficiency. One can compensate the loss of primaries by modifying the gas mixtures. A prototype with 1 mm gap will be built to test different gas mixtures.
- Although the Micromegas modules will be quite light (about 0.5% X/X_0), at large angles, particles will cross more material. One of the major contributions to the material budget is the 100 μmof FR4. The use of carbon fibre instead of FR4 will be investigated.

2.2 What was achieved?

Analysis of the MAMI beam test In June 2023, several small prototypes (FY22 and FY23 proposals) with different 2D readout patterns have been taken to a beam test in MAMI, with an electron beam of 880 MeV.

A schematic representation of the readout patterns is presented in Figure 2. Two prototypes, D1 and D2, have been equipped with orthogonal strips on a two layer flexible PCB: on D1, pitch varied from 0.5 mm to 1.5 mm, while on D2 the pitch was fixed at 1 mm but the inter-strip gaps varied from 25% to 50% of the pitch. For both D1 and D2, the resistive layer was covering all the active area and had a resistivity of the order of 10 M$\Omega/\square$. Other two prototypes, D3 and D4, have been equipped with pad-like orthogonal strips, a similar design as the one used for the Micromegas used in the ASACUSA experiment. The resistive

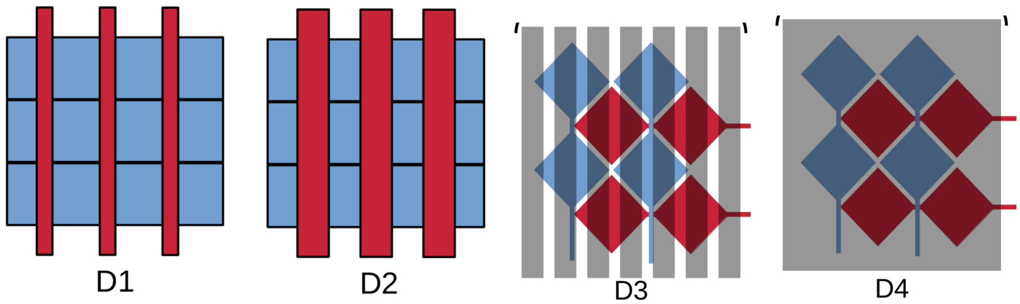

Figure 2: Schematic views of the 2D readout patterns tested. See text for details.

layer of D4 was covering the whole active area with a resistivity of less than 1 M$\Omega/\square$. D3, instead, had a resistive strips (pitch 500 μm) running parallel to one of the two readout strips.

In Figure 3, it is possible to see the arrangement of the beam test. A reference tracker built from four spare ALPIDE Silicon pixel ladders from the ALICE MFT (assembled in Saclay) has been placed at the beam exit window. The test prototypes have been installed on a moving table so that it was possible to remotely change the impinging position of the beam on the detectors. The detectors were at a distance of D1=30.5 cm, D2=42.5 cm, D3=54.5 cm and D4=78.5 cm.

Due to the low energy electron beam, the multiple scattering dominates the measurements of the residues, as shown in Figure 3 where the residues measured in data are overlaid with the ones from a Geant4 simulation that only accounts for the multiple scattering (no digitization). The residues for different strip pitches are shown in Figure 4. The results are not corrected for multiple scattering: since this effect dominates the measurement, its subtraction would lead to large systematic uncertainties related to the Geant4 simulation. The analysis of the spatial resolution for these prototypes will be finalized with the cosmic rays test bench in Saclay.

To achieve similar performances on both readout coordinates, we aim at having an equal sharing of the signal amplitude. The comparison of the amplitude fraction between D1 and D2 shows that an intermediate inter-strip pitch would be preferable, shown in Figure 4. The amplitude fraction of D3 and D4 (the ASACUSA-like pattern) is close to 50% as expected and the small deviation from this value is explained by the traces connecting the pads that results in a slightly larger active area for one of the two coordinates.

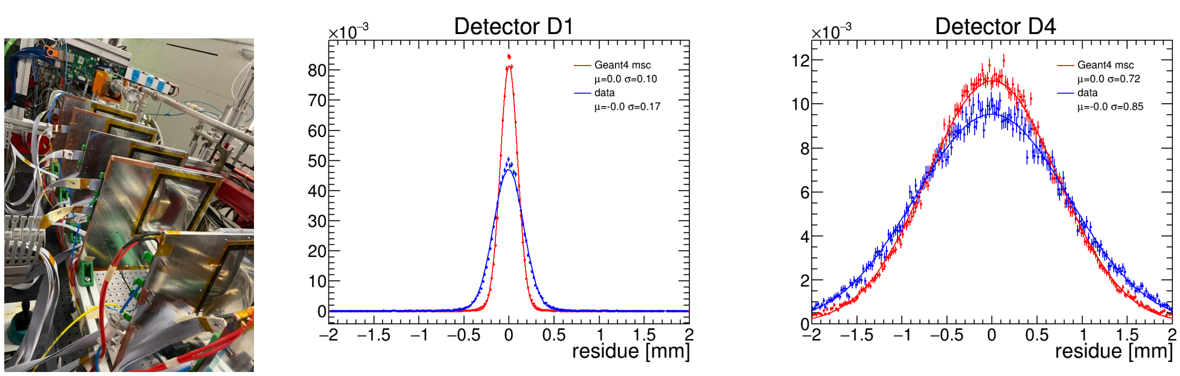

Figure 3: (left) Photo taken at the MAMI beam test showing the reference tracker at the beam line exit and the test detectors on the moving table. (center) Residues for the D1 detector, the closes to the tracker, in data and in a Geant4 simulation. The simulation accounts only for multiple scattering. (right) Residues for the D4 detector, the further from the tracker, in data and in a Geant4 simulation. Plots are normalized.

Cosmics test bench in Saclay The cosmic ray test bench built during the CLAS12 production consists of four 40x40 cm^{2}multiplexed Micromegas detectors for muon reconstruction and the coincidence of two

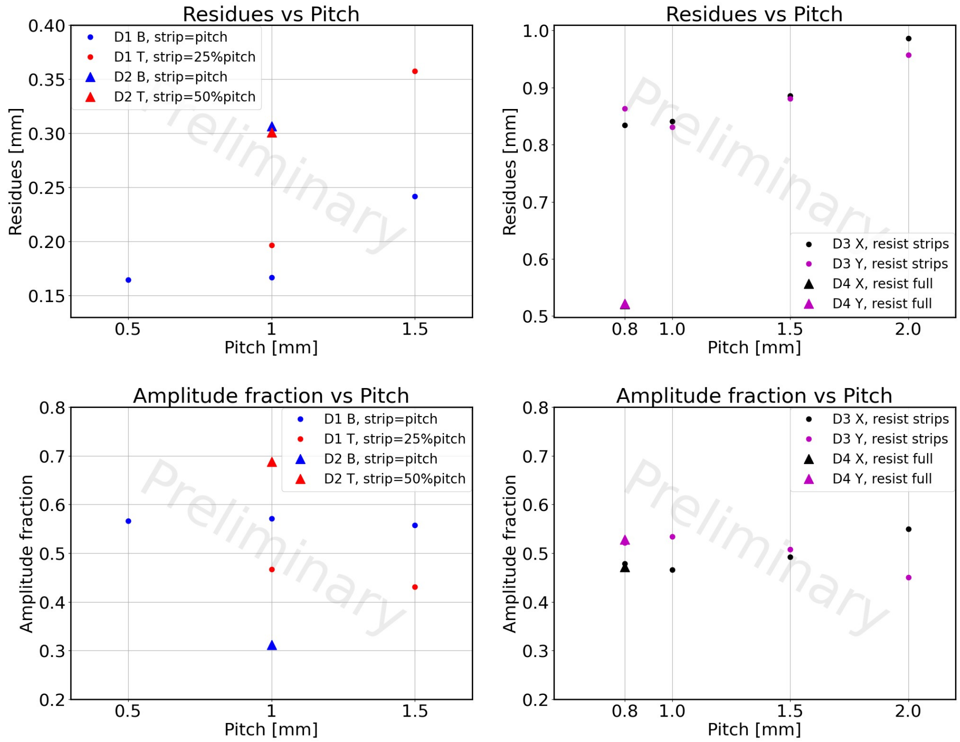

Figure 4: Preliminary results from the beam test data analysis. (top left) Residues for the D1 and D2 detectors as a function of the pitch. In red for the strips of the top layer of the PBC and in blue for the bottom one. (top right right) Residues for the D3 and D4 detectors. Residues are not corrected for the multiple scattering. (bottom left) Signal amplitude fraction between the two orthogonal coordinates for D1 and D2 and (bottom right) D3 and D4.

large scintillators as trigger. The tracking spatial resolution achieved with this setup is about 500 μm.

This test bench has enough available volume to accommodate multiple test detectors at the same time. To preform systematic tests on the Micromegas prototypes for EIC, the test bench has been upgraded to accommodate a stack six small prototypes. In order to achieve a better track resolution, the same silicon hodoscope used in the MAMI test beam has been coupled with the test bench (see Figure 5). Although the active area of the silicon hodoscope is rather small, rate estimates have shown that it will be possible to achieve statistical accuracies better than 10% in less than a day of data taking. The test bench will be used to confirm the results from the test beam and to test additional prototypes that are being produced.

Bulk and bend a CLAS12 PCB In preparation for the building of the large-scale prototype with the selected 2D readout, the production of curved Micromegas is being re-established.

- The mesh tensioning system built for the CLAS12 production has been refurbished (Figure 6). This system allow one to achieve the low values of the micro-mesh tension, of less than 6 N/cm, needed for Micromegas that will be later curved in cylindrical shape.
- A spare CLAS12 PCB has been successfully bulked, without the resistive layer, and bent to the cylindrical shape using the original tooling for the CLAS12 production, as shown in Figure 6. This test Micromegas has passed the high-voltage quality tests.
- Several tests have been dedicated to assess the possibility to use a new photosensitive material for the bulk process. The Pyralux material has been the reference for the production of past detectors. Unfortunately the manufacturer stopped the production and all users are now forced to move to a

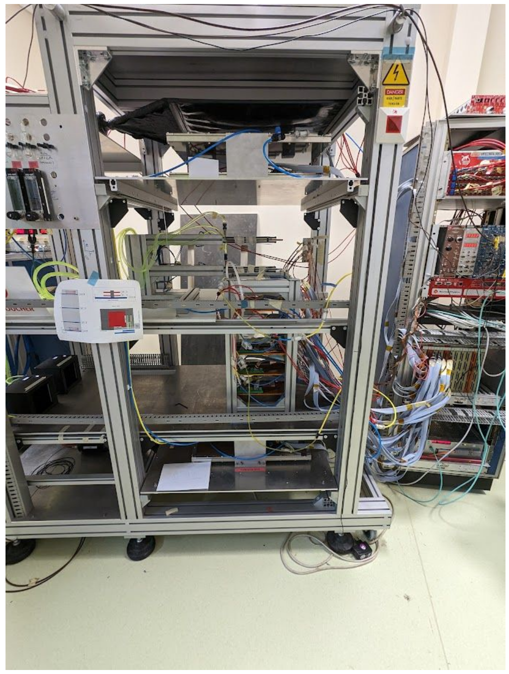

Figure 5: Cosmics test bench in Saclay with the additional Norcan structure to hold up to six prototypes.

different brand. This leads a mandatory R&D for all Micromegas detectors. The Vacrel material had already been successfully used in the past so it was selected as the best option among available ones. However there are many differences between these two photosensitive materials. The main difference is the thickness (64 μm for Pyralux and 50 μm for Vacrel) which leads to a gap between the resistive layer and the mesh of the detector (128 μm down to 100 μm). The composition of the material itself also differs between both options and leads to re-evaluate the full bulking process with adjusting many parameters such as lamination temperature, exposure parameters and development temperature and length time. Successful results were obtained on small metallic detectors ($\sim$10x10 cm^2) but scaling up and adding a resistive layer revealed several technical challenges. Some of them were already met such as different adherence of the photosensitive layer which requires a special surface preparation of the restive layer. Setting adjustments of the machine also allowed to fix rinse issue during the development stage. All these tests were ran on 40x40 cm^2 multiplexed Micromegas detectors as several years of past production experience provide a lot of reference material. A design issue of the resistive layer was also identified as the cause of damage of some resistive strips during the lamination process, this last point requires further investigation and a bit more time to solve. The next step will be to apply it to the exact prototype configuration that were are currently developing. Difference in the gap height also require to be carefully studied.

2.3 What is planned?

The main goal is the completion of the design, the construction and tests of a large scale prototype equipped with the chosen 2D readout pattern, as stated in the FY23 proposal.

The results from the 2023 beam test of different patterns and resistivity layers gave us useful inputs on the charge sharing between the two coordinates as a function of the pattern, but, due to the important multiple scattering, we could not draw firm conclusions on the measurement of the spatial resolution.

To finalise the characterization of the small prototypes, the cosmic rays test bench has been equipped with a stand to test multiple detectors simultaneously and, mainly, it has been coupled with the silicon hodoscope built for the beam test. This addition greatly improves the tracking resolution of the test bench allowing for the completion of the studies on the readout patterns.

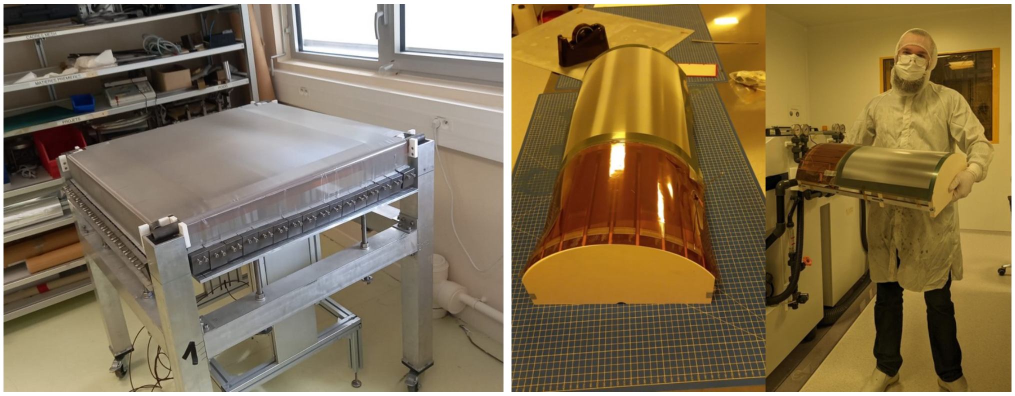

Figure 6: (left) The refurbished micro-mesh tensioning system. (right) A spare CLAS12 PCB bulked with a micromesh and placed on the bending jig in the MPGD Lab at CEA Saclay. This bent Micromegas also passed the high voltage tests.

Due to the change in the photoresistive material used for the bulk, the production of new detectors got delayed. Currently, additional small prototypes are being built to complete the studies on the effect of the resistive layer on the readout pattern resolution. In particular, we will test a resistive grid with 500 μm pitch to get "medium" resistivity values.

For the realisation of the size 1:1 prototype, the following main tasks need to be completed:

- Refurbishing of the production lane for resistive cylindrical Micromegas. As we shown, the realisation of a cylindrical Micromegas using CLAS12 PCBs is undergoing. The completion of this step is instrumental for the 2D prototype.
- Design of the readout PCB. This item depends on the completion of the R&D with small prototypes. Preliminary discussions on how to distribute the high-voltage and the grounding to the resistive layer and the mesh have started.
- Identification of small form factor connector. Due to the constraints in space and material budget, the choice of the connector play an important role in the design. This year we identified a 40-pin connector and its light micro-coaxial cable from KEL as potential candidate. In order to test them, we started the procurement of the connectors and cables of different lengths, and we designed a transition board from the Mec8 connectors used by the CLAS12 FEBs. The connectors and cables will be tested this year with the small prototypes.
- Mechanical design of the prototype. Due to the priority of other projects, we did not start yet the mechanical design. It is planned to be started in Fall 24.

The FY24 R&D proposal included two main aspects: the tests of the gas mixtures with a 1 mm gap prototype and the study on the lighter than FR4 support for the readout PCB.

As planned, the 1-mm gap small prototype requires a small modification to the current design and it is planned to be achieved this Summer. This prototype will allow us to study the efficiency of a 1-mm gap design with different gas mixtures and to study the feasibility of this solution as a measure to counteract the spatial resolution degradation with the angle of the track.

The second aspect is the minimization of the material budget by using alternative materials than FR4. Although with the CLAS12 design we can achieve material budgets of 0.5% of X/X_0 for normal tracks, highly inclined particles will cross more material, therefore reducing further the thickness of the Micromegas modules could benefit the particle reconstruction in ePIC. We started looking for suppliers for $\sim$ 100 μm thick carbon fiber foils, but we plan to give more priority to the completion of 2D readout choice and the size 1:1 prototype production. We will therefore postpone this study in early 2025.

Funding request for FY25 The program described above will bring us to CD3 with a solid design of the cylindrical Micromegas for ePIC. We did not identify further R&D aspects that would require financial support.

3 Cylindrical µRWELL Prototype

3.1 Recap

In the context of R&D on cylindrical MPGDs for tracking in ePIC, a cylindrical micro-Resistive-Well (μRWELL) detector was developed by eRD108. Previous tests of a first prototype for that detector at Fermilab showed that dents would develop over time in the thin curved drift foil. After successfully mitigating the dents by applying higher pressure in the detector, unfortunately, no data could be collected at Fermilab in FY23 due to a laboratory-wide safety shutdown of Fermilab during our test beam period. Since then, FIT and UVa have improved the mechanical stability of the drift foil structure. We plan to perform a test of an improved prototype in a beam test at JLAB in early 2025. Our objective will be to demonstrate that a cylindrical µRWELL detector indeed works and to quantify its tracking performance.

3.2 Improvement of Cylindrical µRWELL Prototype

3.2.1 Mechanical Frame Modification

The rigidity of the drift foil structure has been much increased by developing a technique for gluing a low-mass honeycomb structure to the outside of the curved drift foil (Fig. 7) while maintaining a smooth surface for the inside of that drift cathode. The O-ring for sealing the drift gap has been moved from the drift frame to the spacer frame that defines the drift gap (Fig. 8). The O-ring thickness has been increased to 3 mm to provide better gas tightness of the gas volume of the detector.

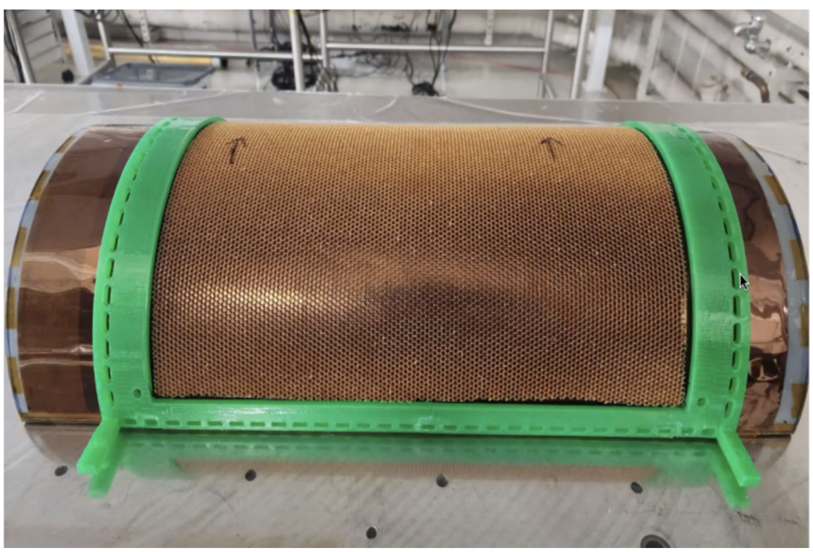

Figure 7: Half-cylinder of µRWELL detector prototype with honeycomb reinforcement glued to the outside of the drift foil made from copper-clad kapton.

3.2.2 Benchtop Testing at FIT

The µRWELL foil with capacitive sharing readout was assembled with the new drift cathode into a second prototype structure. Bench top testing of this structure with high voltage and gas pressure was conducted. The drift foil can hold 1 kV with no warping, denting, or delamination and no discharges were observed. This is a significant improvement in operational stability compared to the original prototype. Two gas pressure

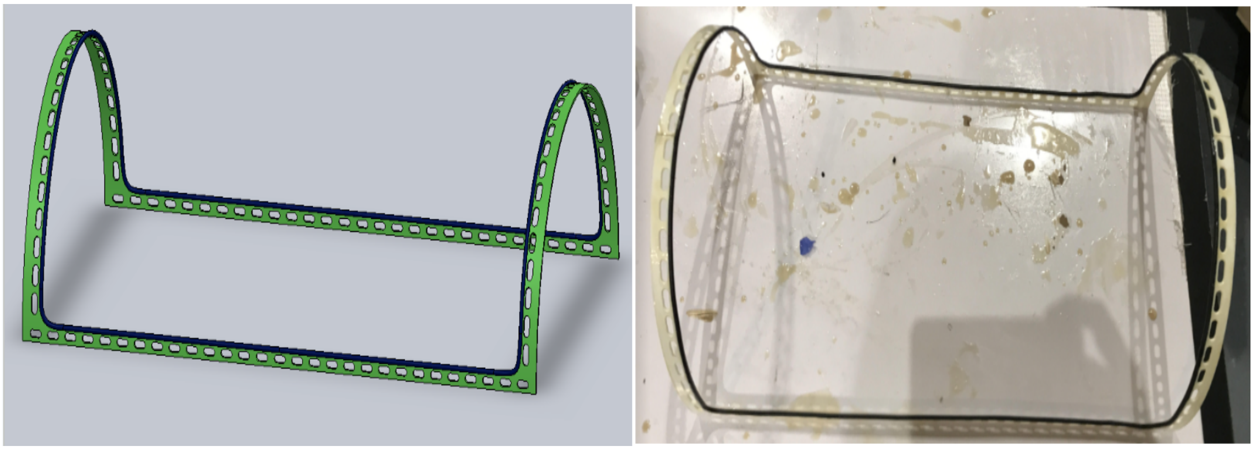

Figure 8: Design (left) and prototype (right) of new drift gap spacer frame.

trial tests were performed with and without the µRWELL foil. The first trial employed a 300 µm mock-up foil instead of the µRWELL foil and the structure successfully held gas pressure with a measured pressure drop from 20 to 10 mbar in 60 minutes. In the second trial, that used the actual µRWELL foil, the gas pressure decreased over the same range in only 2 minutes. The leaking was possibly due to the O-ring being too small and we have remedied this with a larger O-ring as described above.

High Voltage testing of the µRWELL foil showed small leakage currents up to 350 V applied. At 375 V a sudden current increase was observed (Fig. 9). It is suspected that the cause is microscopic debris on the µRWELL foil, possibly dust from ambient air adhering to the µRWELL during assembly or aluminum flakes detaching from the drift foil. We have inquired with CERN about methods for removing this debris. This is currently the critical path for the further development of this prototype and the current focus of our work. Additional future work includes producing the honeycomb reinforcement for the drift foil of the other half-cylinder and possibly replacing the aluminum mylar drift foil with a copper-clad kapton foil.

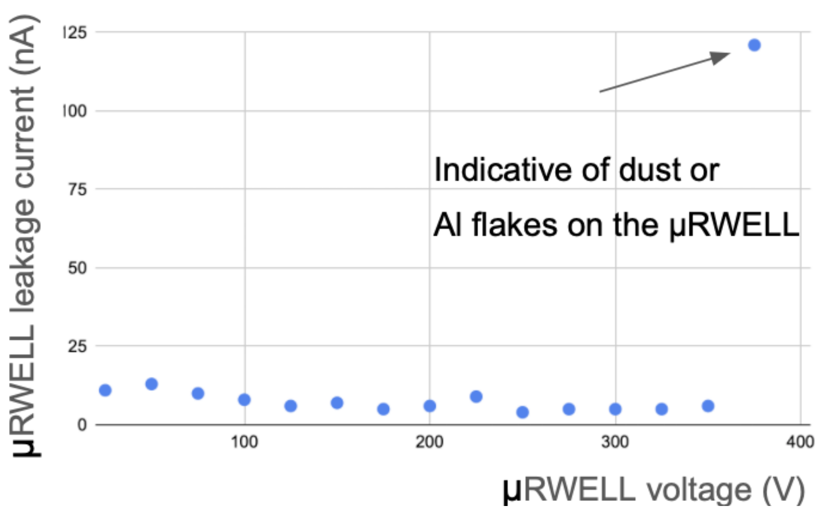

Figure 9: Measured leakage current vs. applied high voltage during bench top testing of the half-cylinder µRWELL prototype and readout foil at FIT.

3.3 Plans and FY25 Funding Request

3.3.1 Beam Test at JLAB

We plan to test the performance of the full refurbished prototype cylinder with the two readout halves in the 12 GeV electron beam at JLAB in early 2025. **To enable this effort, we are hoping that modest funding can be made available to support travel by Ph.D. student Pietro Iapozzuto to JLAB to conduct this test over two weeks with technical support from Kondo Gnanvo. We estimate the total cost for Pietro's transportation, housing, and per diem, as well as for shipping of detectors and equipment to and from JLAB at <u>10 k$ including indirect cost</u>.**